Report B03

Project status and frst results to constrain NMEs for fundamental symmetries

Principal Investigators:

Prof. Dr. Joachim Enders
Dr. Volker Werner

Doctoral students:

Udo Gayer
Philipp Ries

Supported by DFG
research grant CRC 1245

Project B03
Constraining nuclear matrix elements for fundamental symmetries

TECHNISCHE UNIVERSITÄT DARMSTADT

Atomic nuclei as testing ground for weak processes

Neutrinoless double beta decay	WIMP – nucleus scattering
$\lambda_{0\nu\beta\beta}\left(\langle {}^{A}_{Z+2}X \,|\, V_{weak} \,|\, {}^{A}_{Z}X \rangle,\ m_{\nu}\right)$	$\sigma_{(WIMP,\ WIMP)}\left(\langle {}^{A}_{Z}X^{*} \,|\, V_{weak} \,|\, {}^{A}_{Z}X \rangle,\ m_{WIMP},\ S_{WIMP},\ ..\right)$

Project B03

Constraining nuclear matrix elements for fundamental symmetries

TECHNISCHE UNIVERSITÄT DARMSTADT

Atomic nuclei as testing ground for weak processes

Neutrinoless double beta decay

WIMP – nucleus scattering

$$\lambda_{0\nu\beta\beta}\left(\langle {}^{A}_{Z+2}X \,|\, V_{weak} \,|\, {}^{A}_{Z}X \rangle,\ m_{\nu}\right)$$

$$\sigma_{(WIMP,\ WIMP)}\left(\langle {}^{A}_{Z}X^{*} \,|\, V_{weak} \,|\, {}^{A}_{Z}X \rangle,\ m_{WIMP},\ S_{WIMP},\ ..\right)$$

High sensitivity detection experiments

Atomic nuclei as testing ground for weak processes

Neutrinoless double beta decay

$$\lambda_{0\nu\beta\beta}\left(\langle {}^{A}_{Z+2}X \,|\, V_{weak} |\, {}^{A}_{Z}X \rangle, m_{\nu}\right)$$

WIMP – nucleus scattering

$$\sigma_{(WIMP,\,WIMP)}\left(\langle {}^{A}_{Z}X^{*} | V_{weak} | {}^{A}_{Z}X \rangle, m_{WIMP}, S_{WIMP}, ..\right)$$

High sensitivity detection experiments → Fundamental properties of matter

Project B03

Constraining nuclear matrix elements for fundamental symmetries

TECHNISCHE UNIVERSITÄT DARMSTADT

Atomic nuclei as testing ground for weak processes

Neutrinoless double beta decay

$$\lambda_{0\nu\beta\beta}\left(\langle {}^{A}_{Z+2}X | V_{weak} | {}^{A}_{Z}X \rangle, m_{\nu}\right)$$

WIMP – nucleus scattering

$$\sigma_{(WIMP,\, WIMP)}\left(\langle {}^{A}_{Z}X^{*} | V_{weak} | {}^{A}_{Z}X \rangle, m_{WIMP}, S_{WIMP}, ..\right)$$

High sensitivity detection experiments

Fundamental properties of matter

High-precision nuclear structure information

Outline

- **Nuclear structure and 0νββ decay**
  - Infuence of deformation
  - Investigation of nuclear shapes
  - B03 photon scattering (^{82}Se/^{82}Kr, ^{150}Sm/^{150}Nd)
  - B03 electron scattering (^{76}Ge/^{76}Se)

- **Nuclear structure and WIMPs**
  - B03 electron scattering (^{129}Xe/^{131}Xe)

Nuclear Structure and 0νββ Decay

Infuence of deformation

TECHNISCHE UNIVERSITÄT DARMSTADT

$$\left(T^{0\nu}_{1/2}\right)^{(-1)} = G_{0\nu}(Q_{\beta\beta}, Z)\,|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Phase space factor

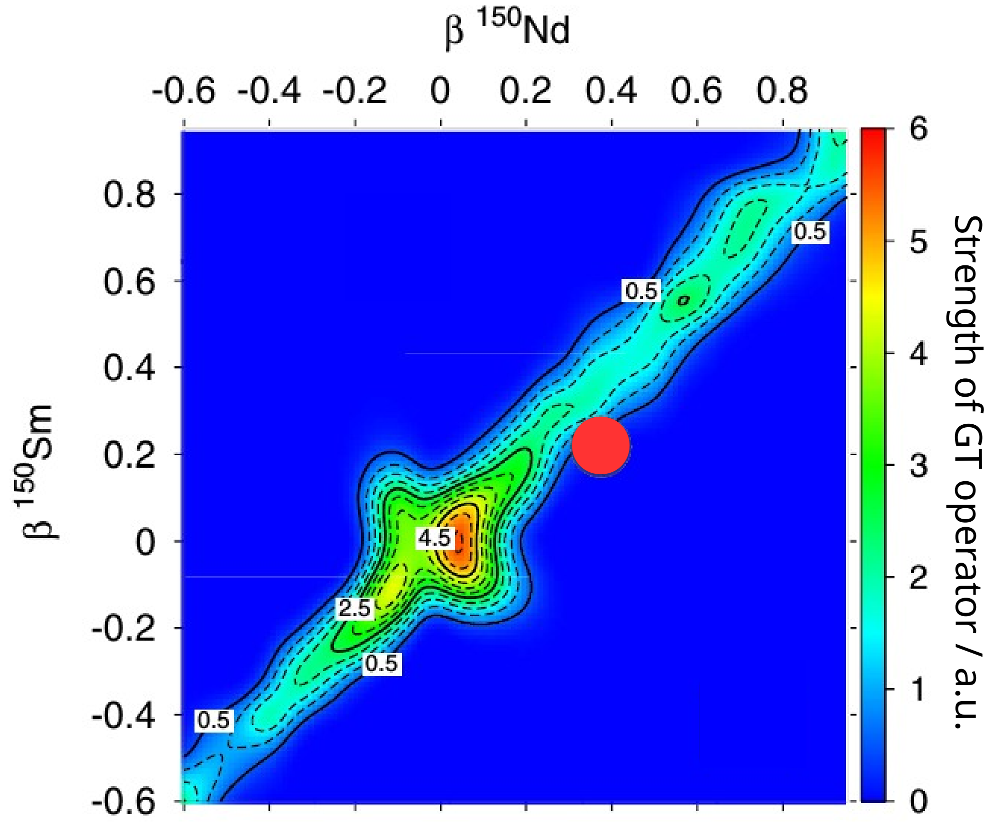
Nuclear Matrix Element (NME)

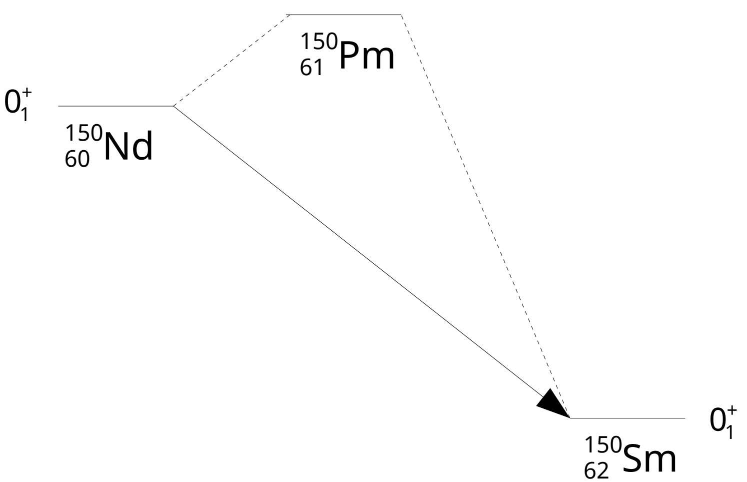
Effective ν mass

Nuclear Structure and 0νββ Decay

Infuence of deformation

$$\left(T_{1/2}^{0\nu}\right)^{(-1)} = G_{0\nu}(Q_{\beta\beta}, Z)\,|M_{0\nu}|^2 \langle m_{\beta\beta}\rangle^2$$



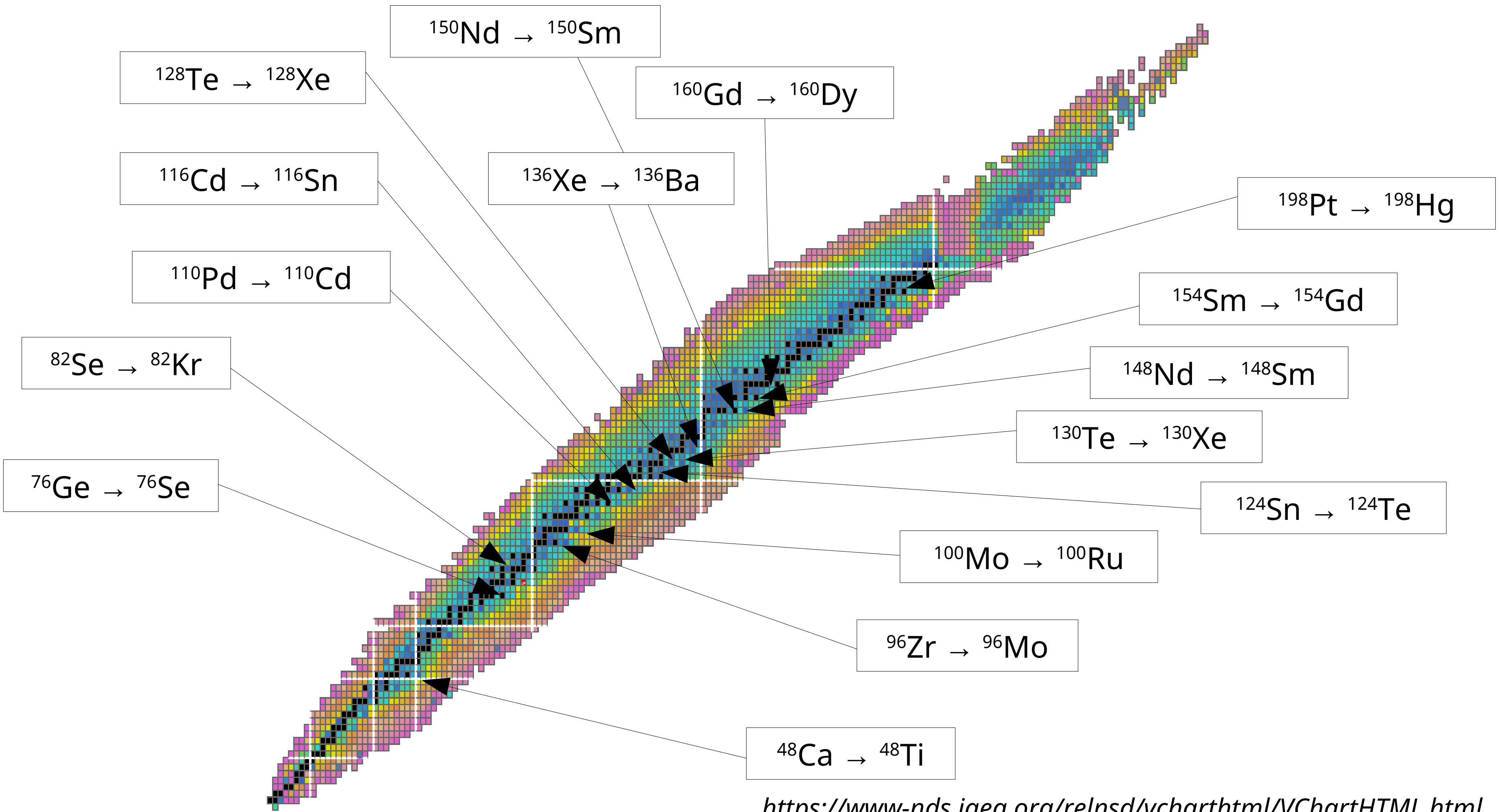


T. R. Rodríguez, G. Martínez-Pinedo, Phys. Rev. Lett. **105** (2010) 252503

Nuclear Structure and 0νββ Decay

Candidates

TECHNISCHE UNIVERSITÄT DARMSTADT



https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

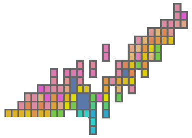
Set of Nuclei from: J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 87 (2013) 014315

Nuclear Structure and 0νββ Decay
Candidates

^{150}Nd → ^{150}Sm

^{128}Te → ^{128}Xe

^{160}Gd → ^{160}Dy

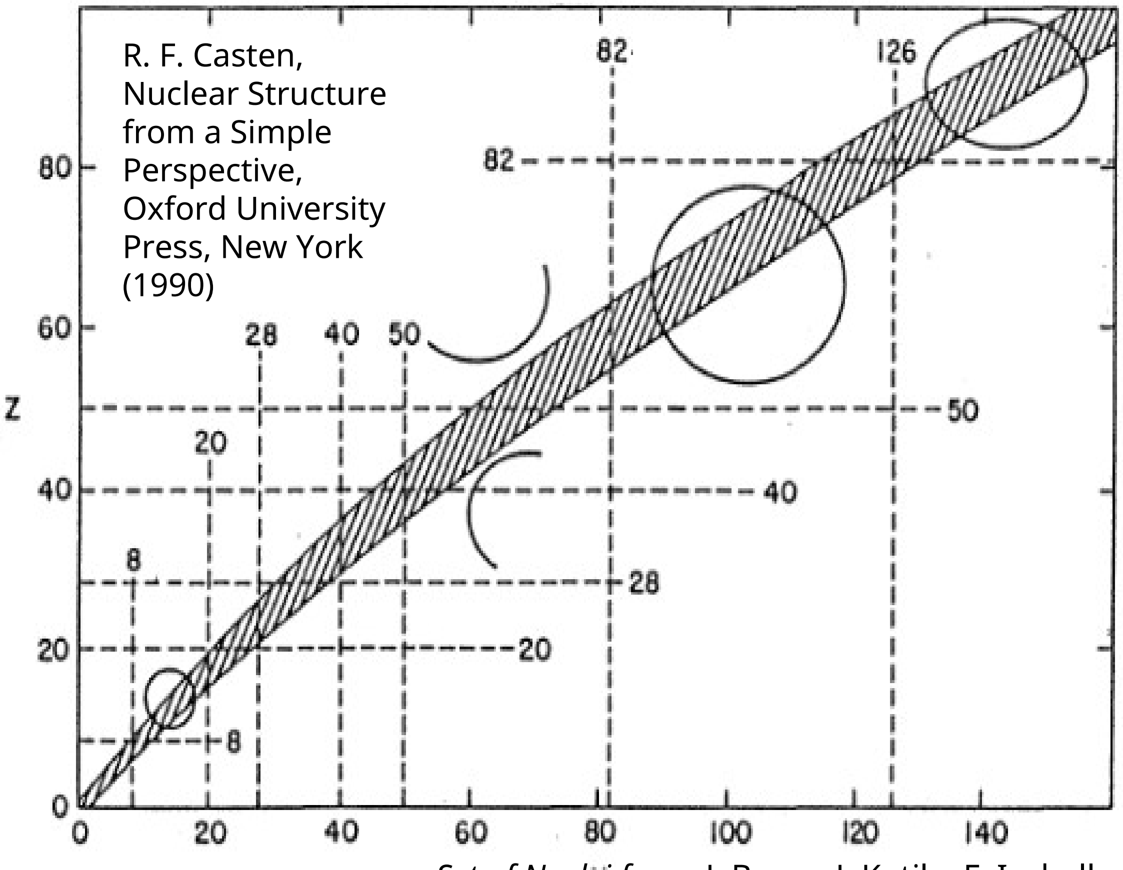


116(

11(

^{82}Se → ^{82}K(

^{76}Ge → ^{76}Se



^{198}Pt → ^{198}Hg

^{154}Sm → ^{154}Gd

^{148}Nd → ^{148}Sm

→ ^{130}Xe

^{124}Sn → ^{124}Te

d/vcharthtml/VChartHTML.html

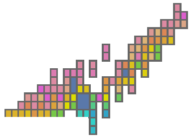
Set of Nuclei from: J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 87 (2013) 014315

Nuclear Structure and 0νββ Decay
Candidates

$^{128}Te \rightarrow {}^{128}Xe$

$^{150}Nd \rightarrow {}^{150}Sm$

$^{160}Gd \rightarrow {}^{160}Dy$

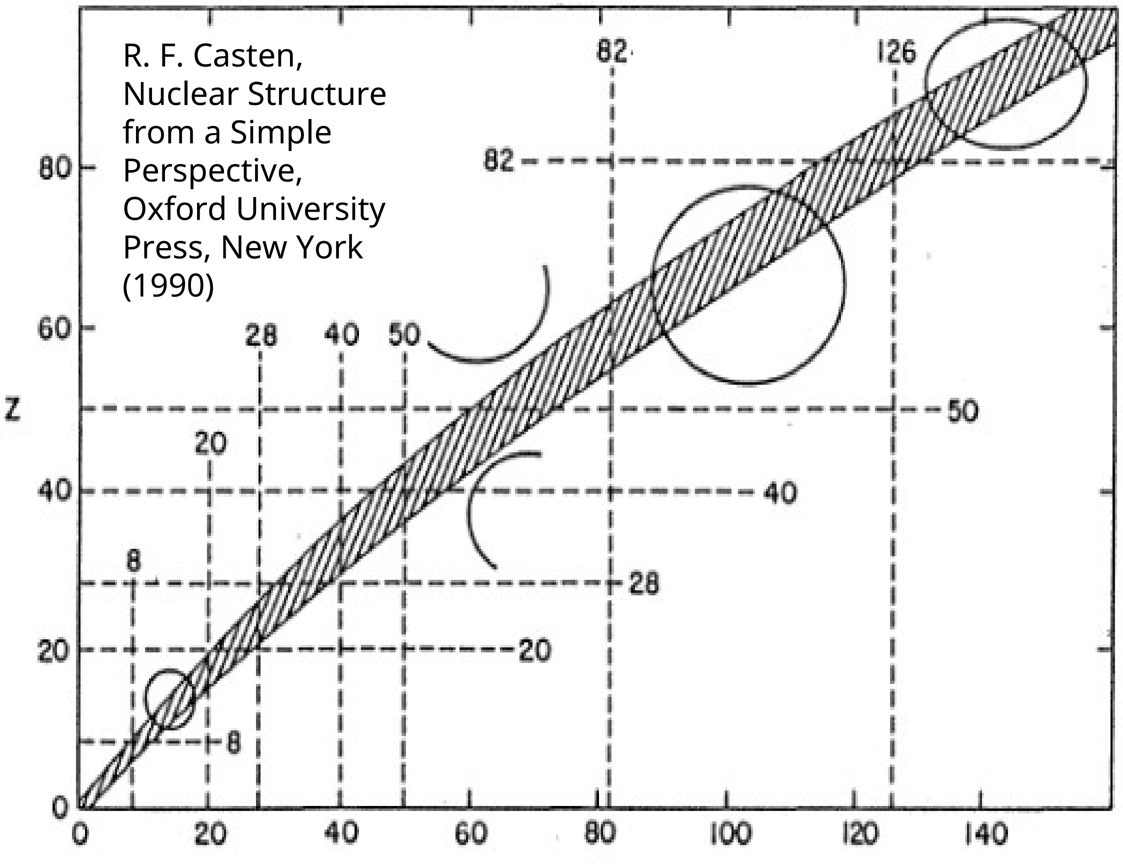


116(

11(

$^{82}Se \rightarrow {}^{82}$K

$^{76}Ge \rightarrow {}^{76}Se$



$^{198}Pt \rightarrow {}^{198}Hg$

$^{154}Sm \rightarrow {}^{154}Gd$

$^{148}Nd \rightarrow {}^{148}Sm$

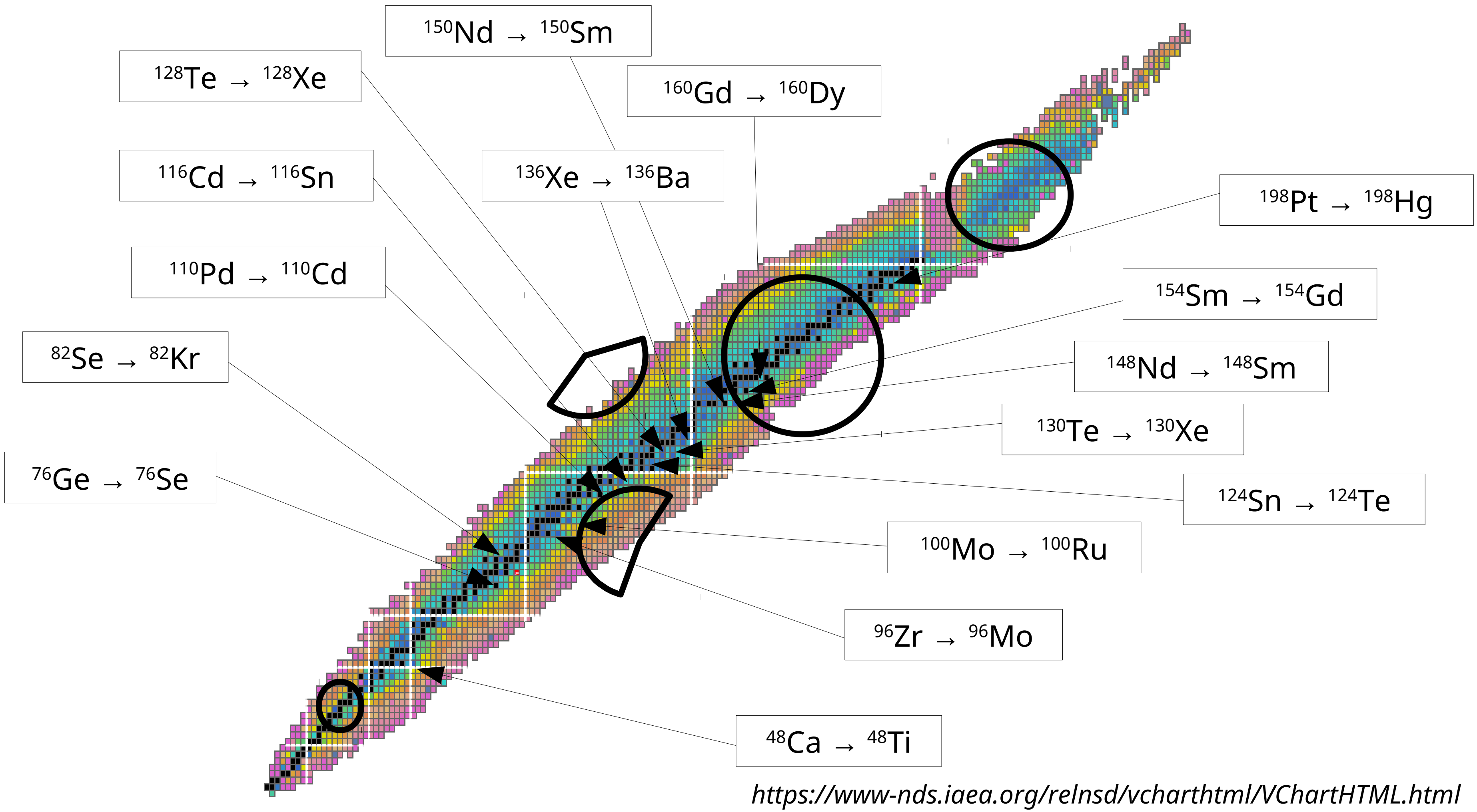
$\rightarrow {}^{130}Xe$

$^{124}Sn \rightarrow {}^{124}Te$

l/vcharthtml/VChartHTML.html

Set of Nuclei from: J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 87 (2013) 014315

Nuclear Structure and 0νββ Decay
Candidates



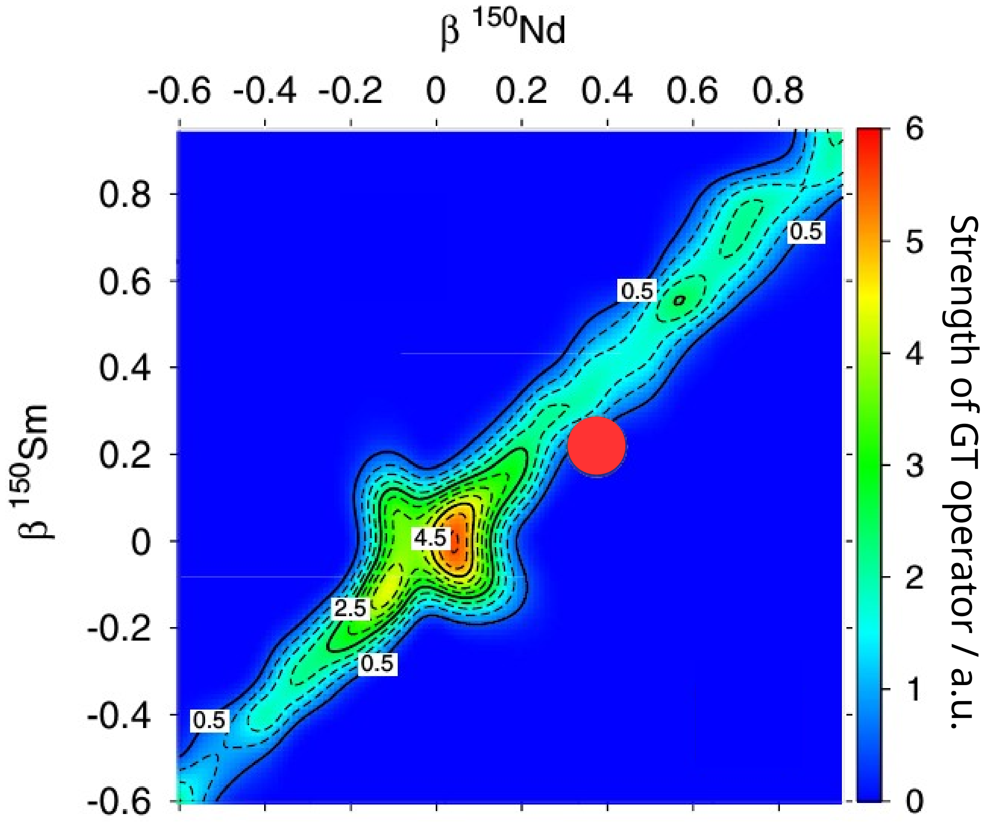
https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

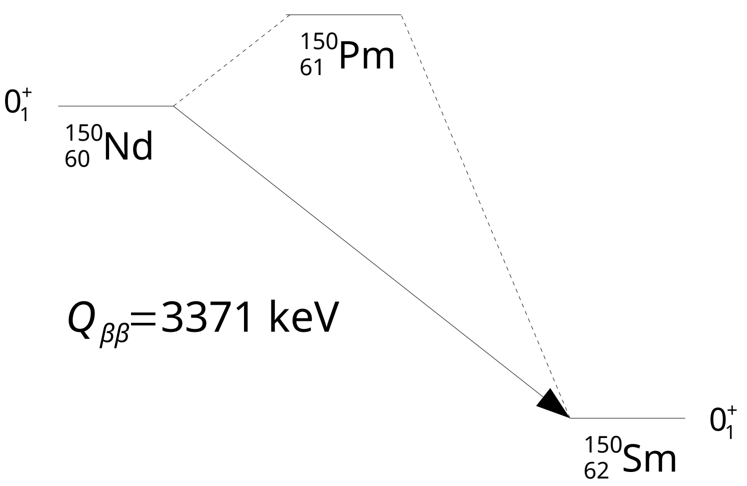
Set of Nuclei from: J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 87 (2013) 014315

Nuclear Structure and 0νββ Decay

Infuence of deformation

$$\left(T^{0\nu}_{1/2}\right)^{(-1)} = G_{0\nu}(Q_{\beta\beta}, Z)\,|M_{0\nu}|^2 \langle m_{\beta\beta}\rangle^2$$

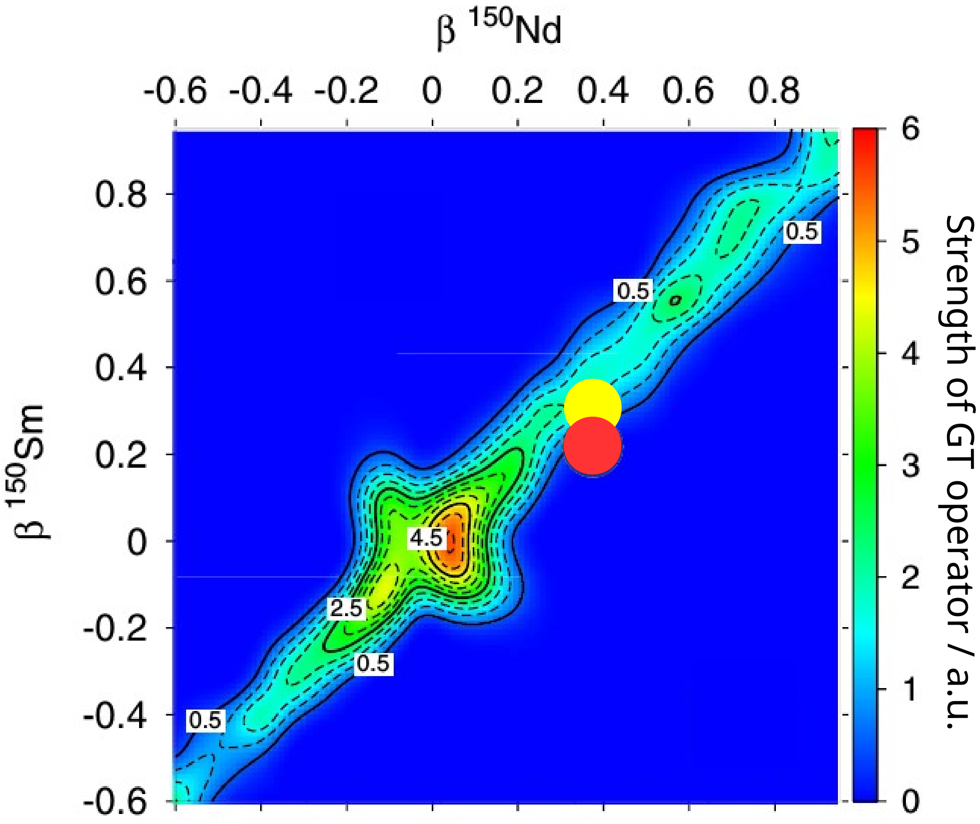


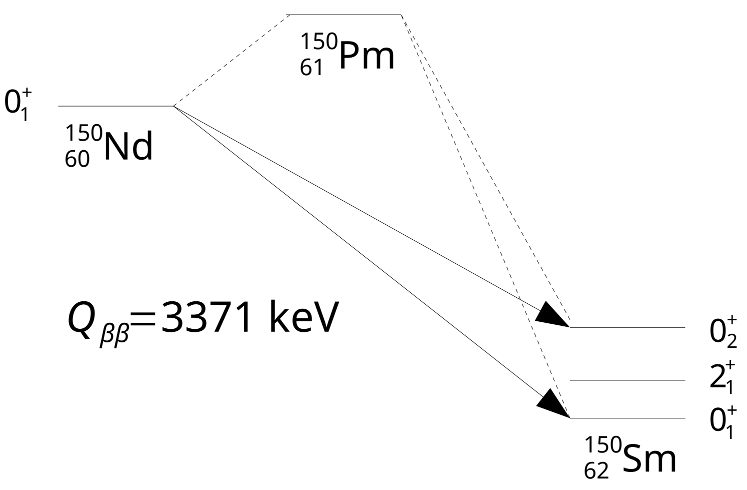


T. R. Rodríguez, G. Martínez-Pinedo, Phys. Rev. Lett. **105** (2010) 252503

Nuclear Structure and 0νββ Decay
Infuence of deformation

$$\left(T^{0\nu}_{1/2}\right)^{(-1)} = G_{0\nu}(Q_{\beta\beta}, Z)\,|M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$



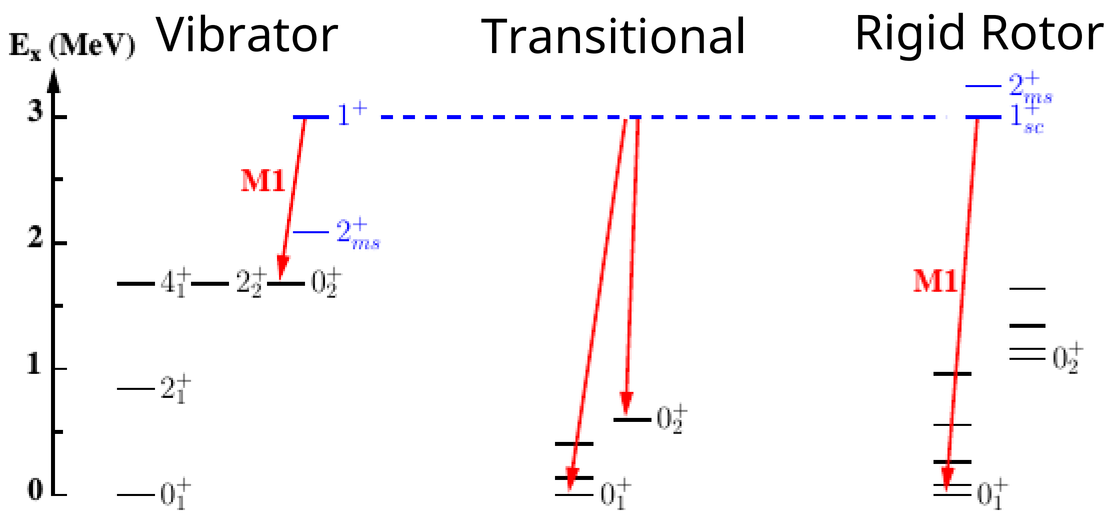


T. R. Rodríguez, G. Martínez-Pinedo, Phys. Rev. Lett. **105** (2010) 252503

Nuclear Structure and 0νββ Decay
Investigation of nuclear shapes

TECHNISCHE UNIVERSITÄT DARMSTADT

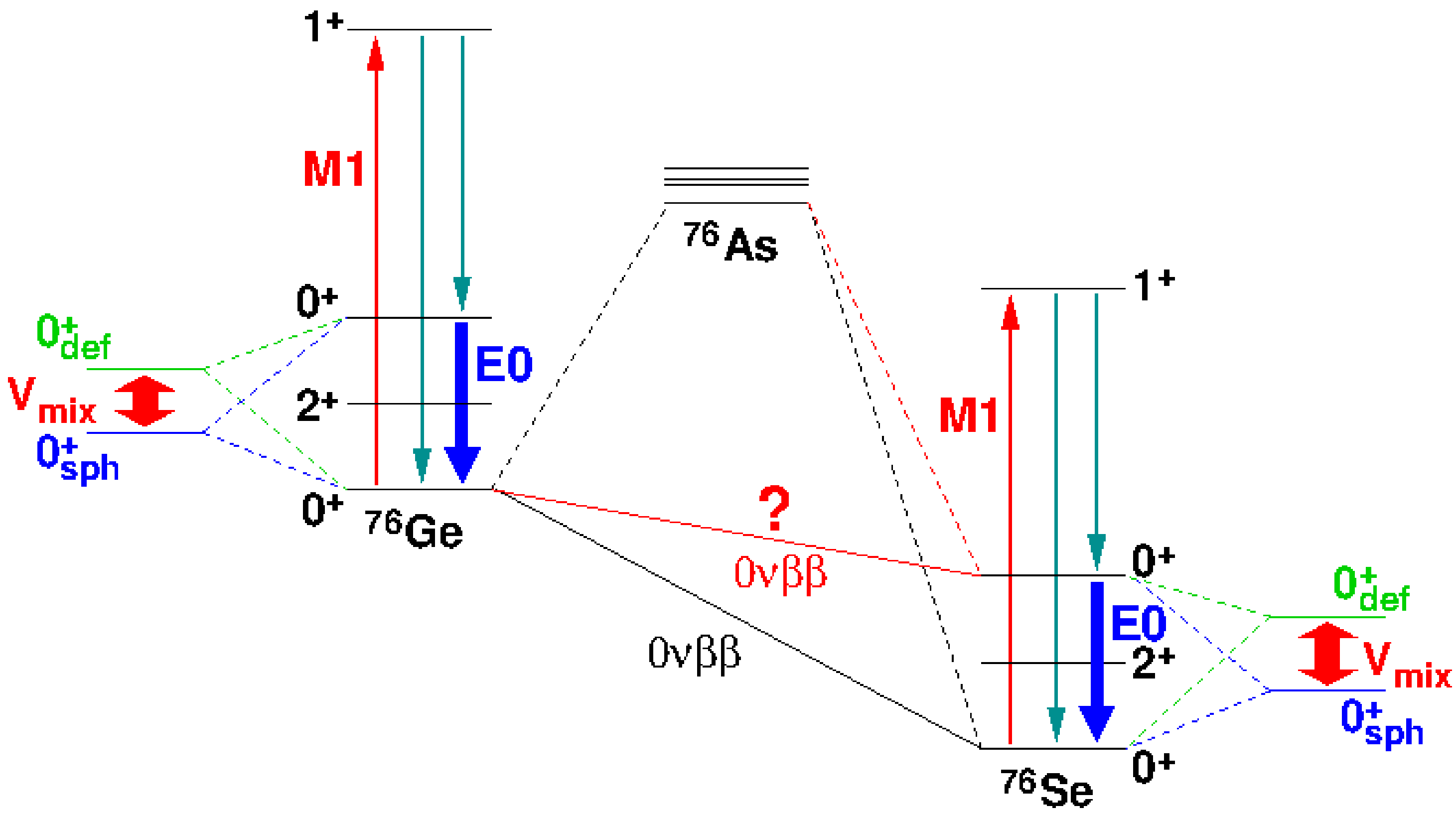
- Sensitivity to nuclear shapes / shape transitions
  → Decay of 1⁺ mixed-symmetry states / scissors mode



J. Beller, Dissertation, TU Darmstadt (2014)

Nuclear Structure and 0νββ Decay
Investigation of nuclear shapes

- Sensitivity to nuclear shapes / shape transitions
  - → Decay of 1^+ mixed-symmetry states / scissors mode
  - → E0 transitions to excited 0^+ states



Motivation

0νββ decay, Detection experiments

$^{136}Xe \rightarrow {}^{136}Ba$

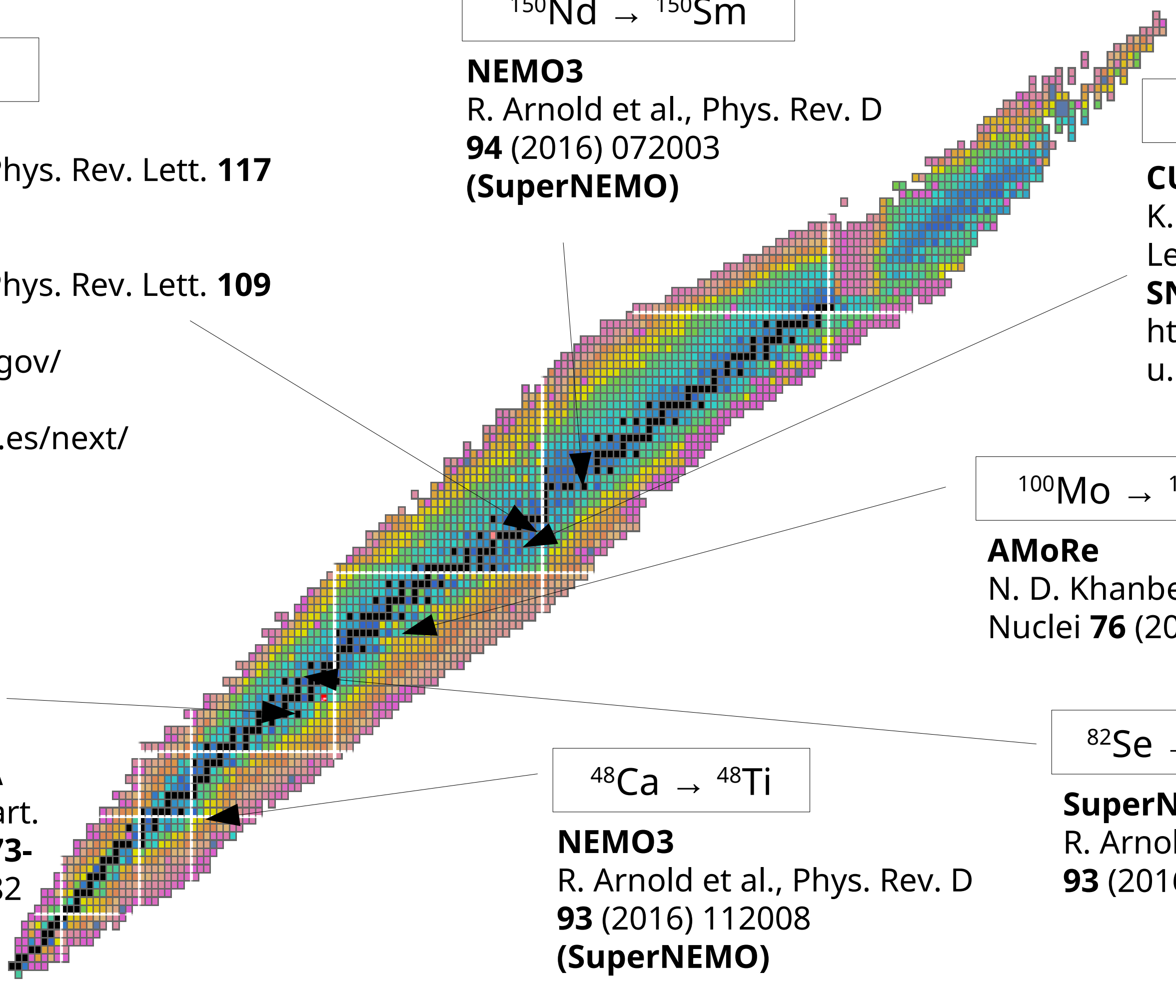
KamLAND-Zen
A. Gando et al., Phys. Rev. Lett. **117** (2016) 082503
EXO/nEXO
M. Auger et al., Phys. Rev. Lett. **109** (2012) 032505
https://nexo.llnl.gov/
NEXT
http://next.ifc.uv.es/next/

$^{150}Nd \rightarrow {}^{150}Sm$

NEMO3
R. Arnold et al., Phys. Rev. D **94** (2016) 072003
(SuperNEMO)

$^{130}Te \rightarrow {}^{130}Xe$

CUORE
K. Alfonso et al., Phys. Rev. Lett. **115** (2015) 102502
SNO+
http://snoplus.phy.queensu.ca/Home.html



$^{100}Mo \rightarrow {}^{100}Ru$

AMoRe
N. D. Khanbekov, Phys. Atom. Nuclei **76** (2013) 1086

$^{76}Ge \rightarrow {}^{76}Se$

GERDA/MAJORANA
M. Agostini et al., Part. Nucl. Phys. Proc., **273-275** (2016) 1876-1882
N. Abgrall et al., AHEP, **2014** (2014) 365432

$^{48}Ca \rightarrow {}^{48}Ti$

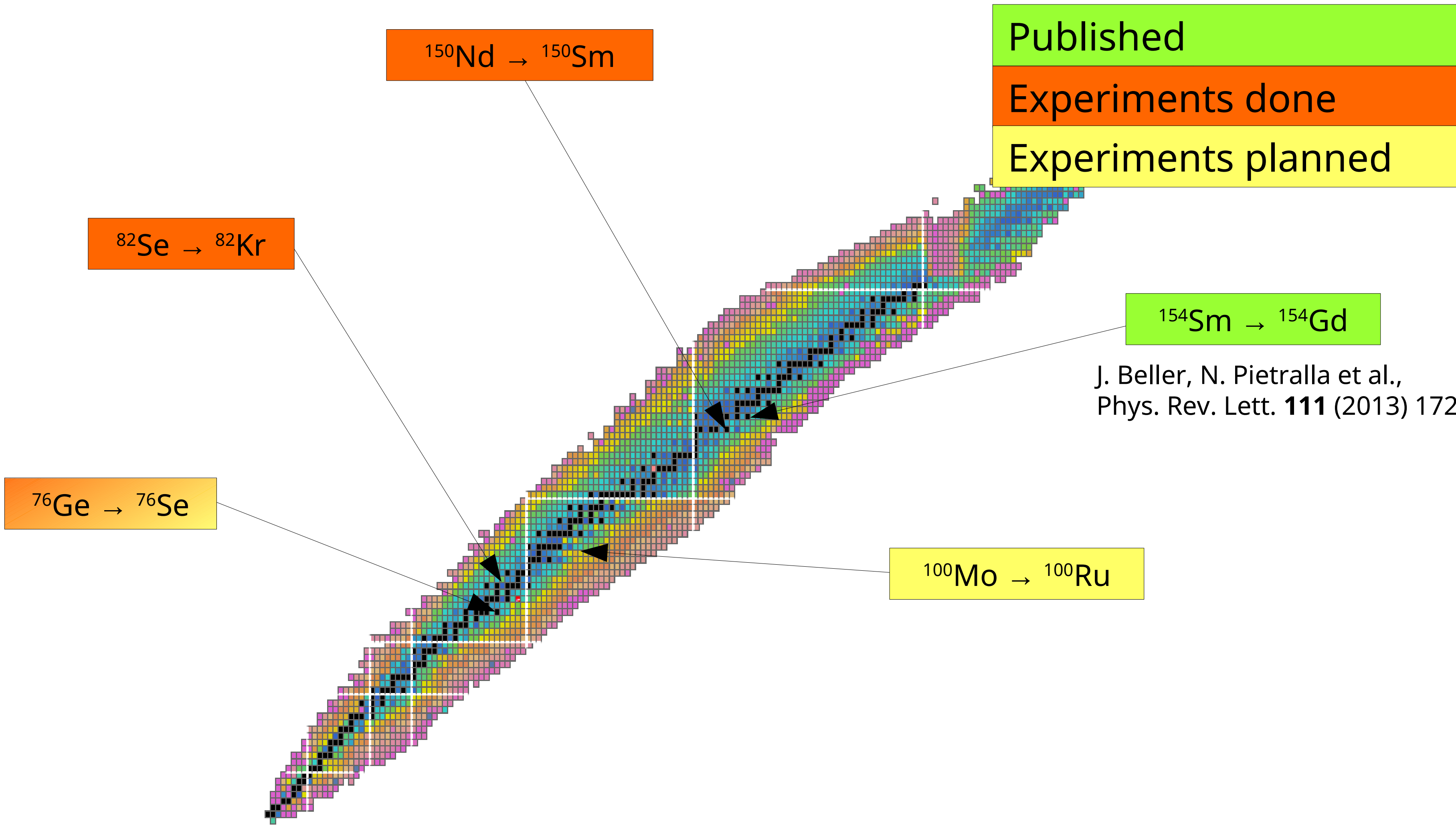
NEMO3
R. Arnold et al., Phys. Rev. D **93** (2016) 112008
(SuperNEMO)

$^{82}Se \rightarrow {}^{82}Kr$

SuperNEMO
R. Arnold et al., Phys. Rev. D **93** (2016) 112008

https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

Nuclear Structure and 0νββ Decay
B03 experimental program



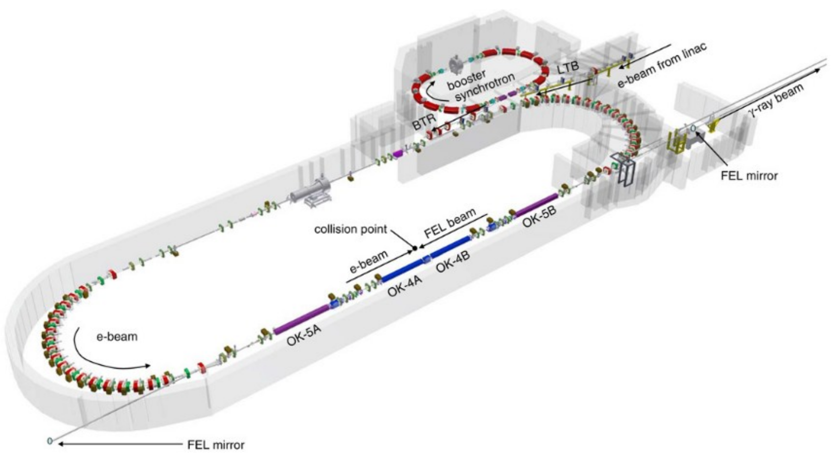
J. Beller, N. Pietralla et al., Phys. Rev. Lett. **111** (2013) 172501

https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

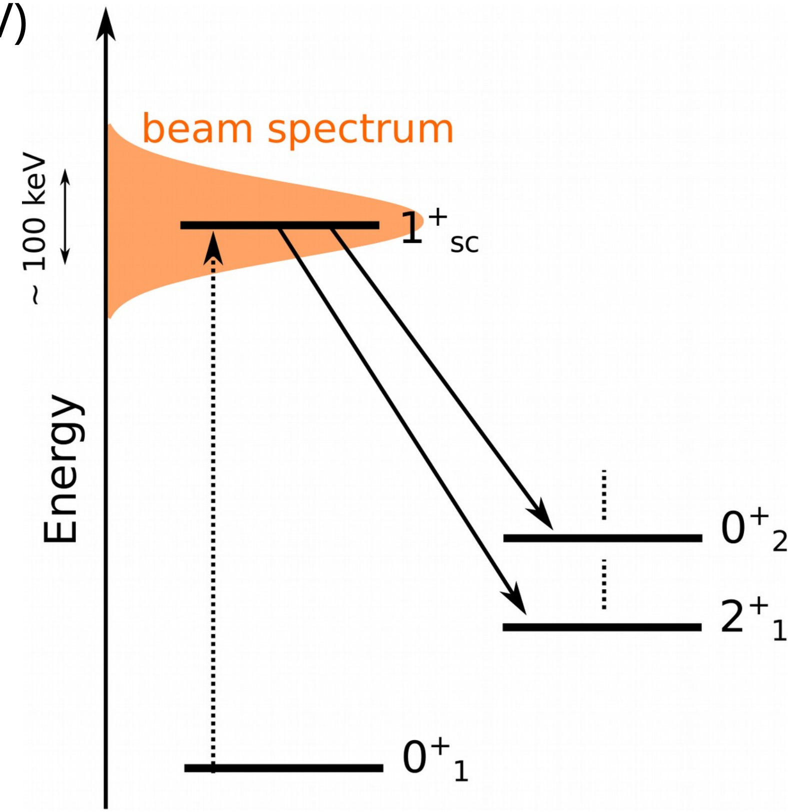
B03 Photon Scattering

- High-Intensity Gamma-Ray Source (HIγS) @ Duke University, Durham, NC, USA
  → Quasi-monoenergetic, linearly polarized photon beam
- (Still) most intense gamma-ray source in the world
  (10^7 γ/s at 3 MeV, beam FWHM ~100 keV)

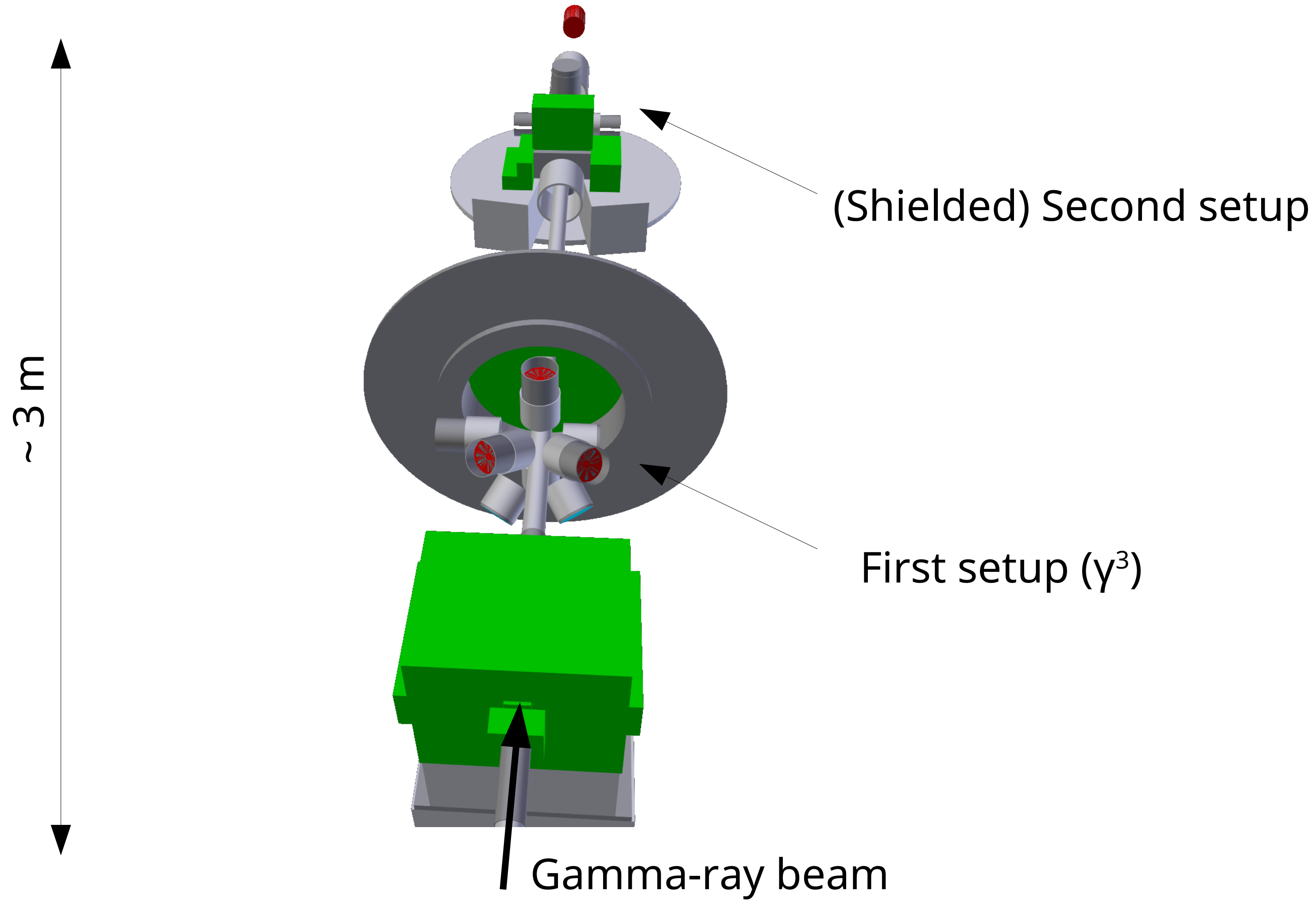
http://www.tunl.duke.edu/documents/public/HIGSBeamParameters.pdf



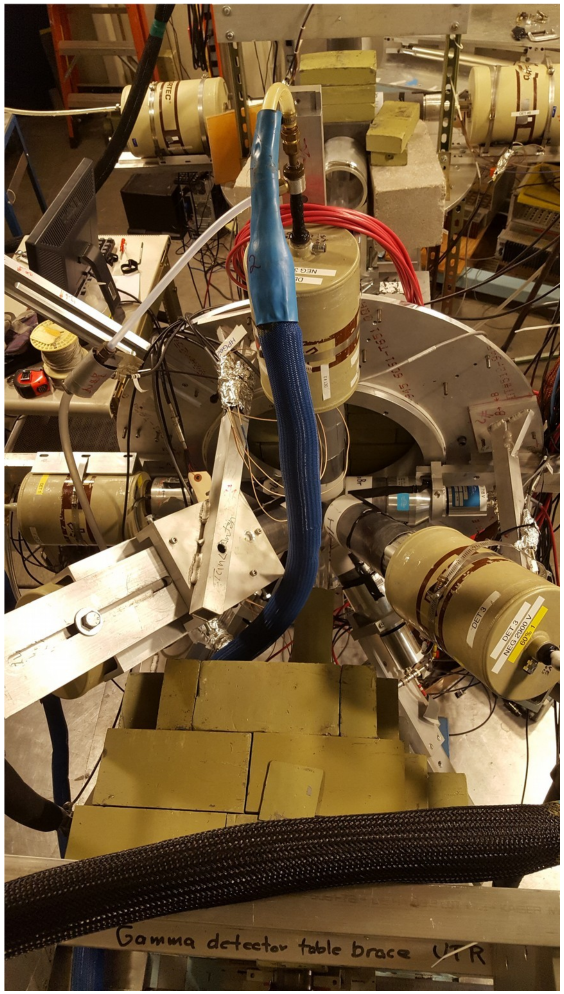
H. Weller et al., Prog. Part. Nucl. Phys. (2009) 257-303

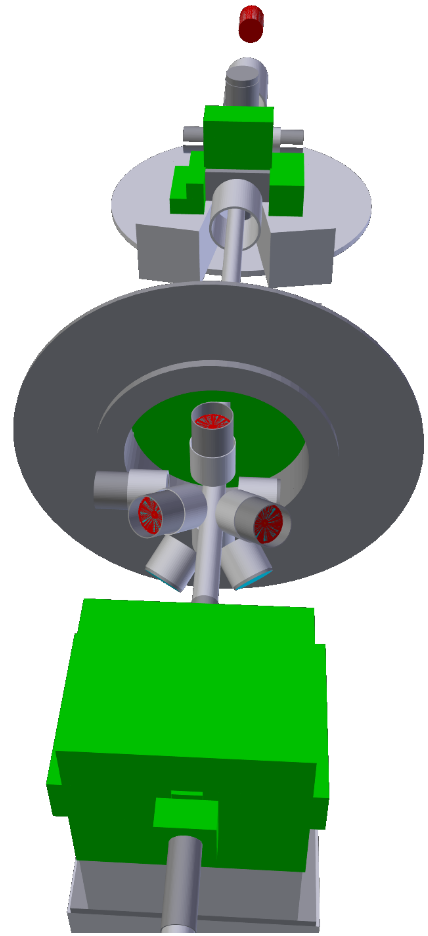


B03 Photon Scattering



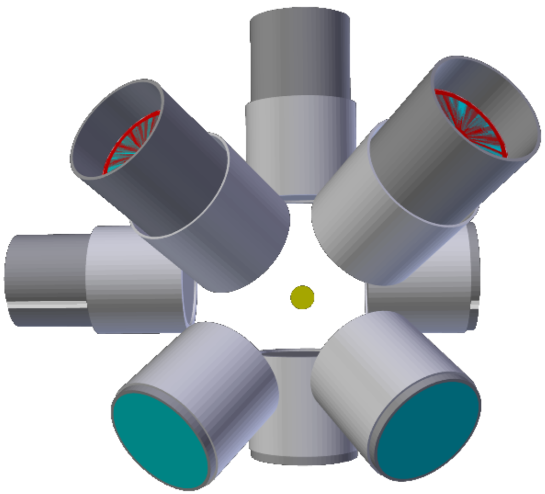
B03 Photon Scattering





B03 photon scattering

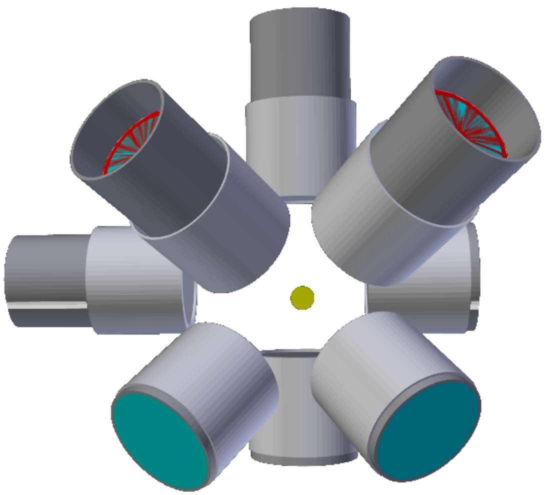
- γ^3 setup (^{82}Se, ^{150}Nd)
  B. Löher et al., Nucl. Inst. Meth. A 723 (2013) 136-142

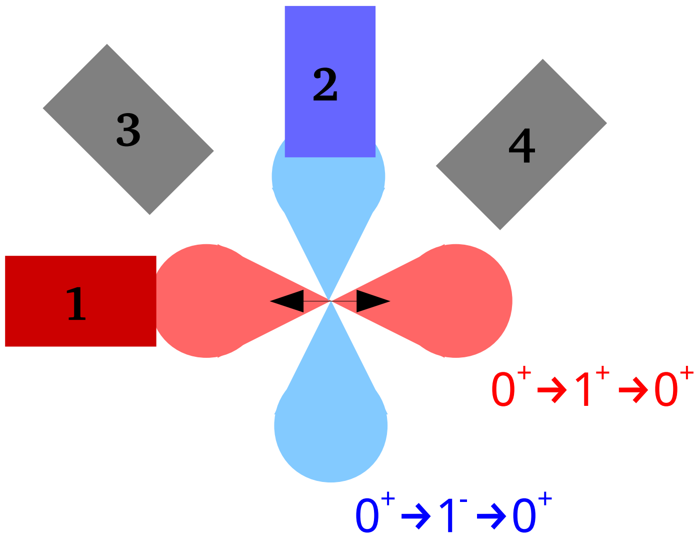


- 4 x 60% HPGe
  - Efficiency: ~0.2%
  - Energy Resolution: ~ 3 keV
  - Time Resolution: ~ 1 ns
- 4 x 3x3" LaBr(Ce)
  - Efficiency: ~1 % @ 1.5 MeV
  - Energy Resolution: ~ 30 keV
  - Time Resolution: ~ 0.1 ns

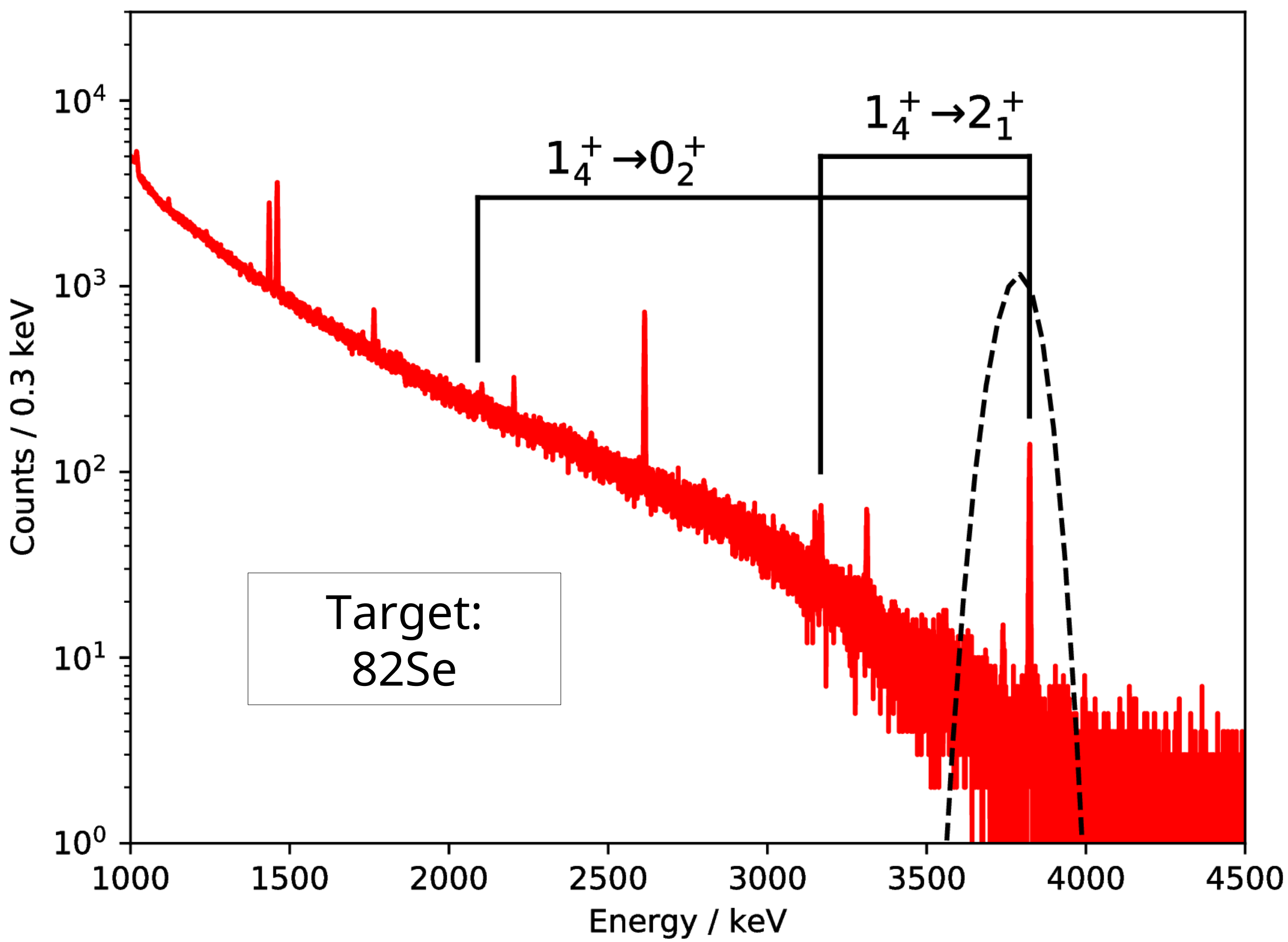
B03 Photon Scattering

- γ^3 setup (^{82}Se, ^{150}Nd)
  B. Löher et al., Nucl. Inst. Meth. A 723 (2013) 136-142

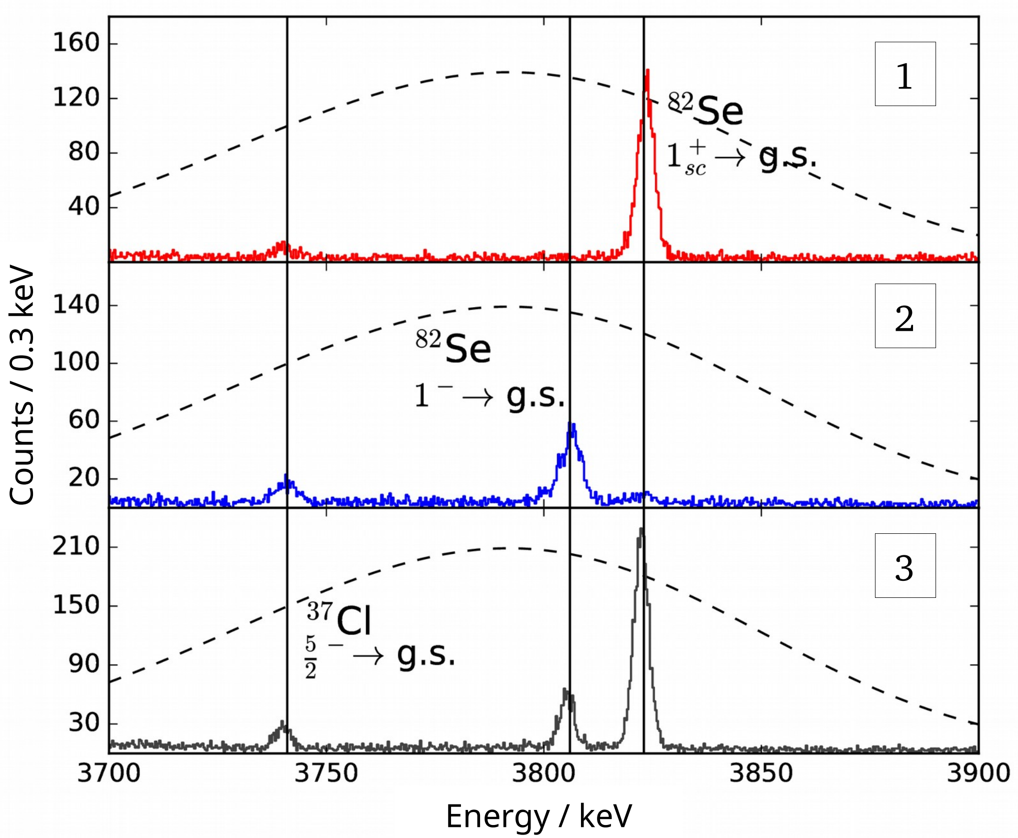


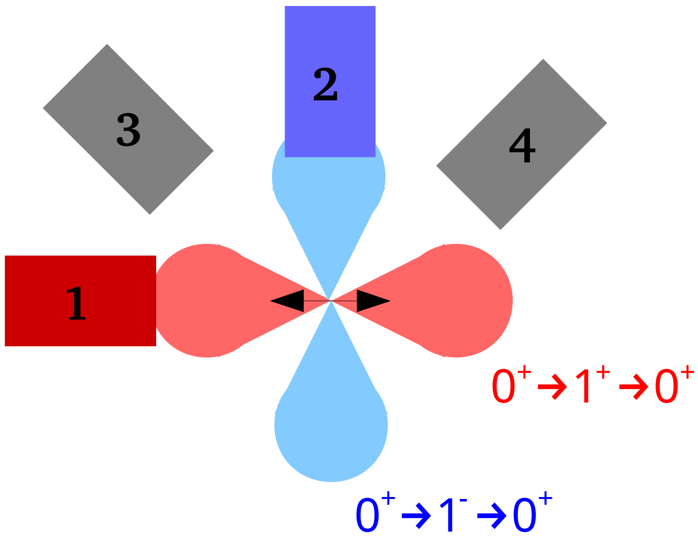


B03 Photon Scattering



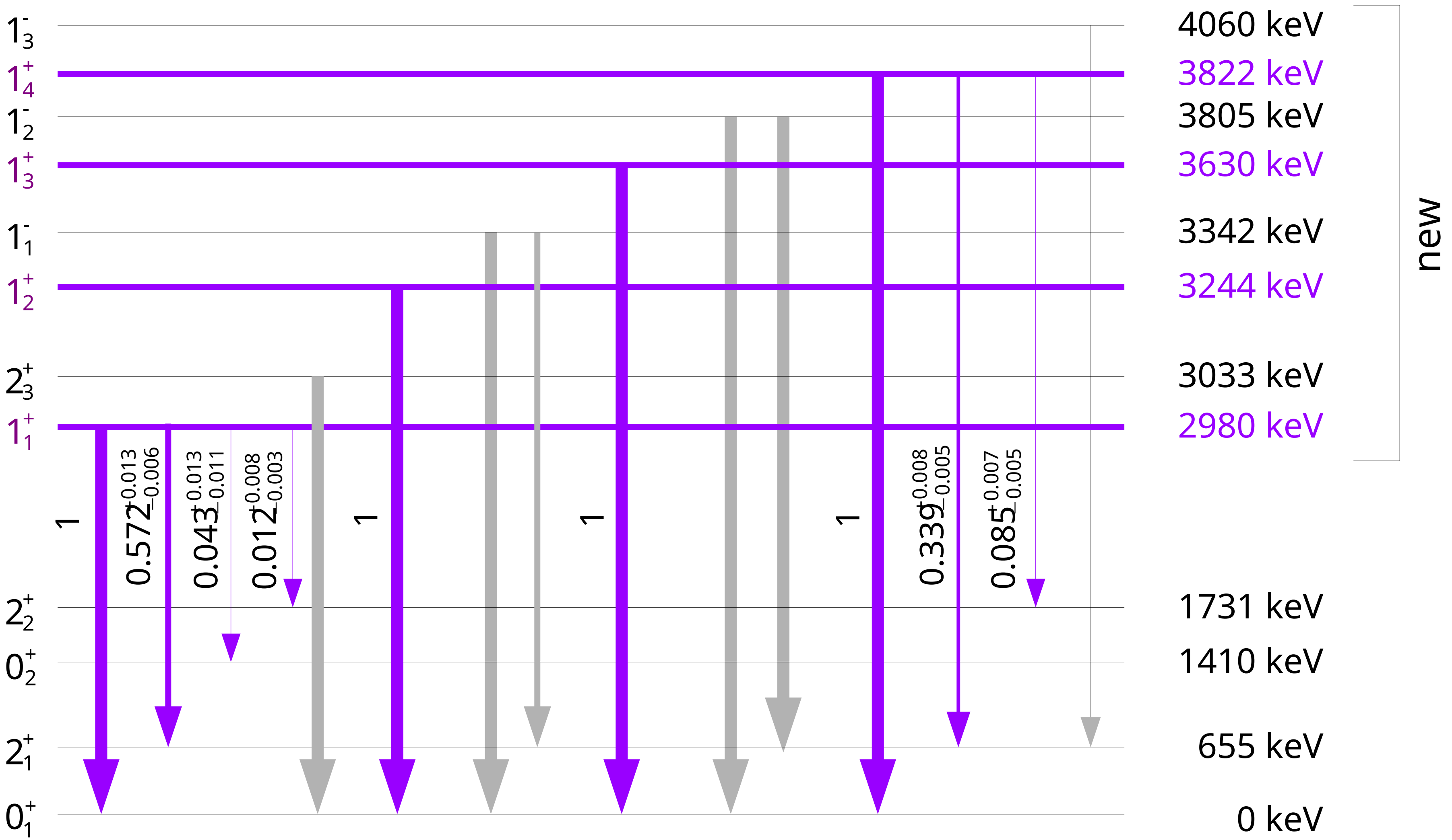
B03 Photon Scattering



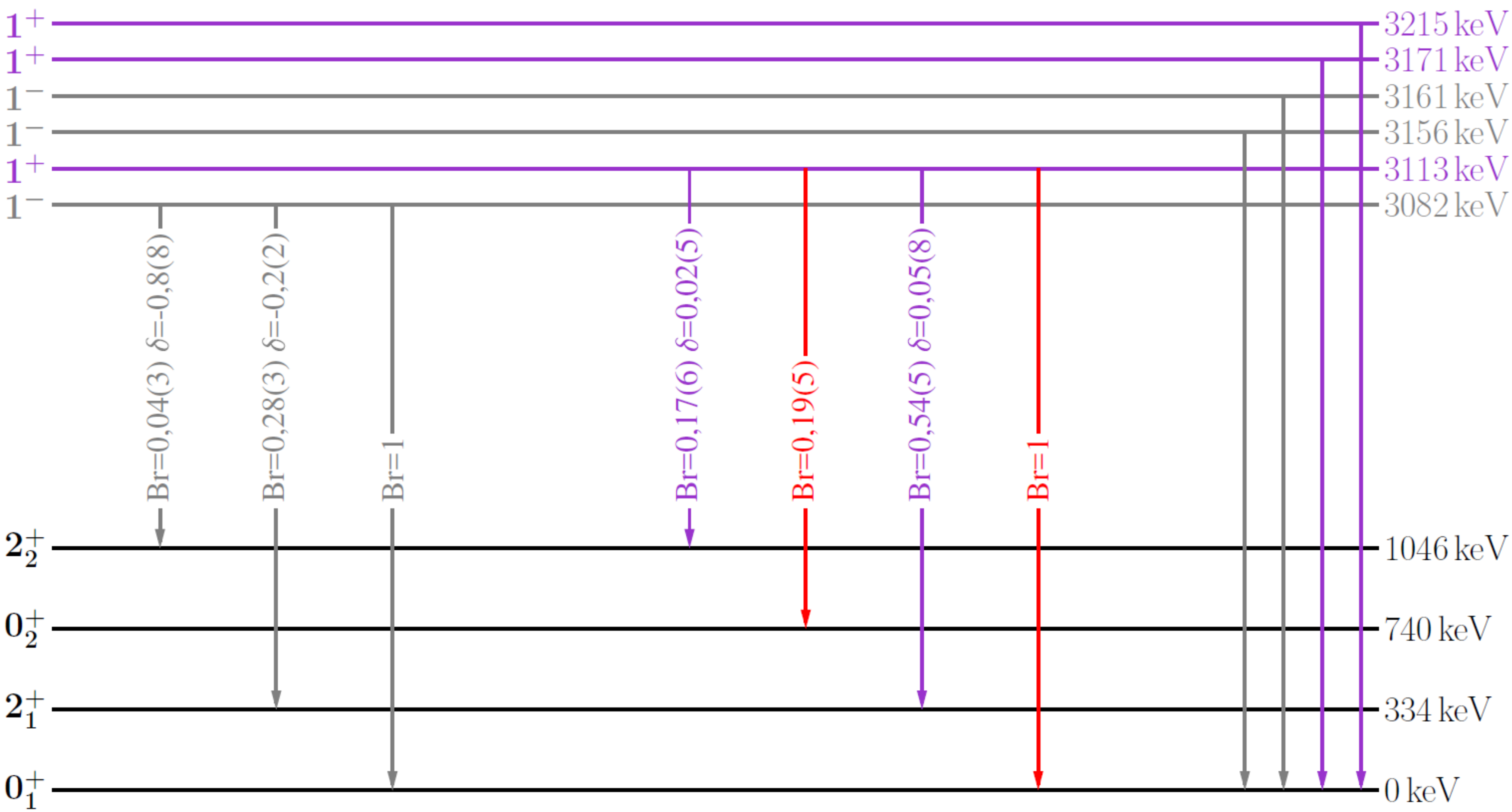


B03 Photon Scattering

Decay branchings ^{82}Se

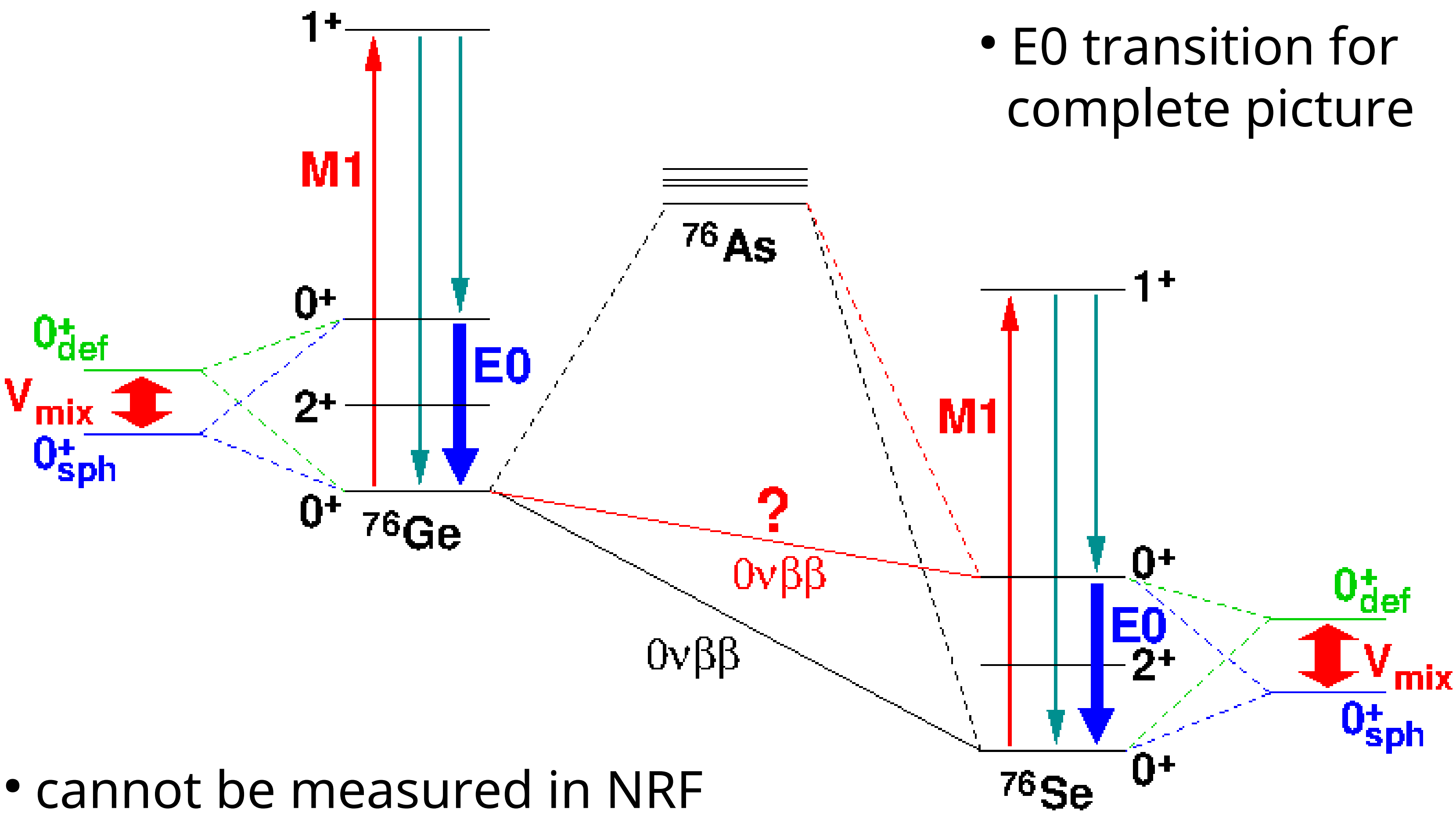


B03 Photon Scattering
Decay branchings ^{150}Sm



J. Kleemann, BSc Thesis (2016)

Connection to Electron Scattering

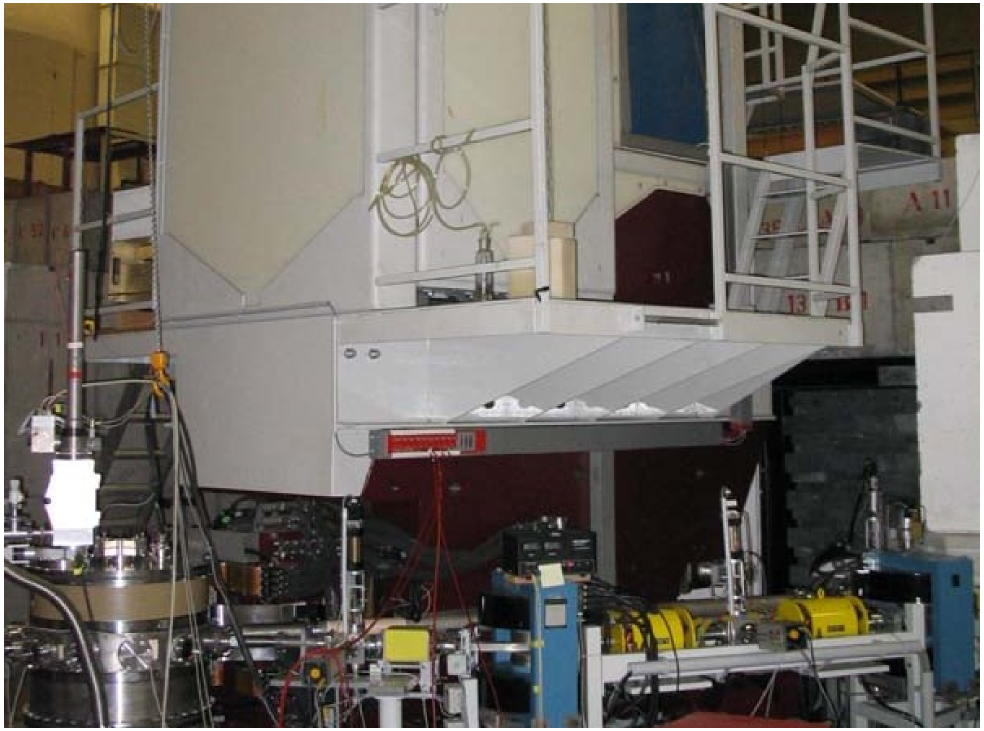


- E0 transition for complete picture

- cannot be measured in NRF
- possible in electron scattering

Electron Scattering Experiments at QCLAM

- measurements of $0\nu\beta\beta$ partners ^{76}Ge and ^{76}Se at QCLAM spectrometer at S-DALINAC
- utilizing large acceptance
- extracting form factors of 0^+_1 and 0^+_{gs}
- *E0* transition strength
- up to 3 weeks beam time



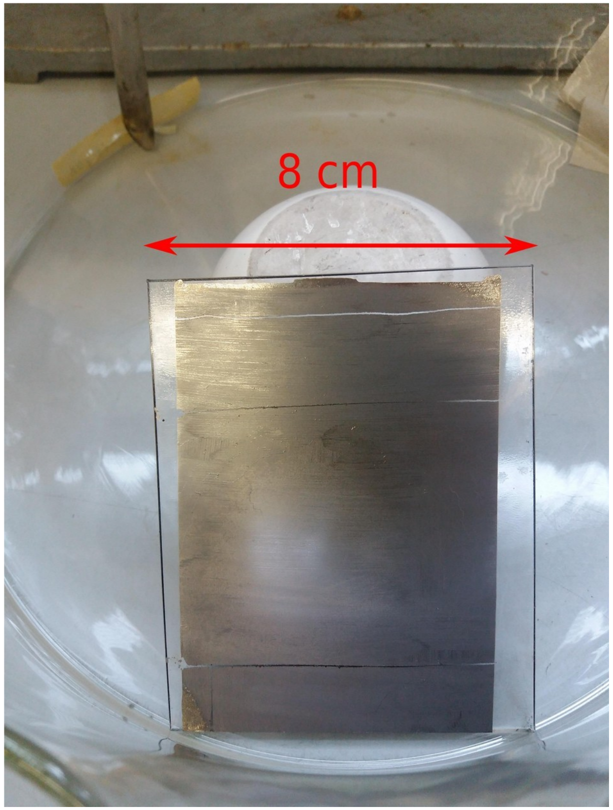
Status Target Production

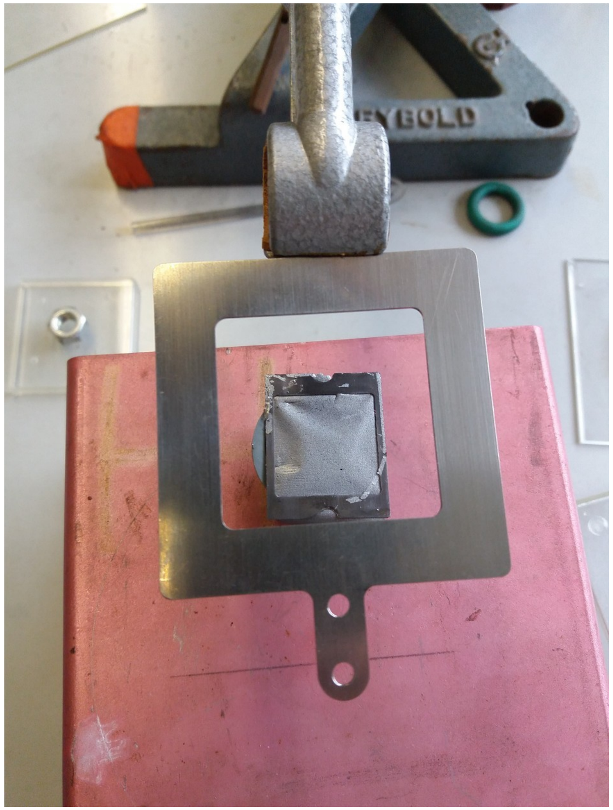
TECHNISCHE UNIVERSITÄT DARMSTADT

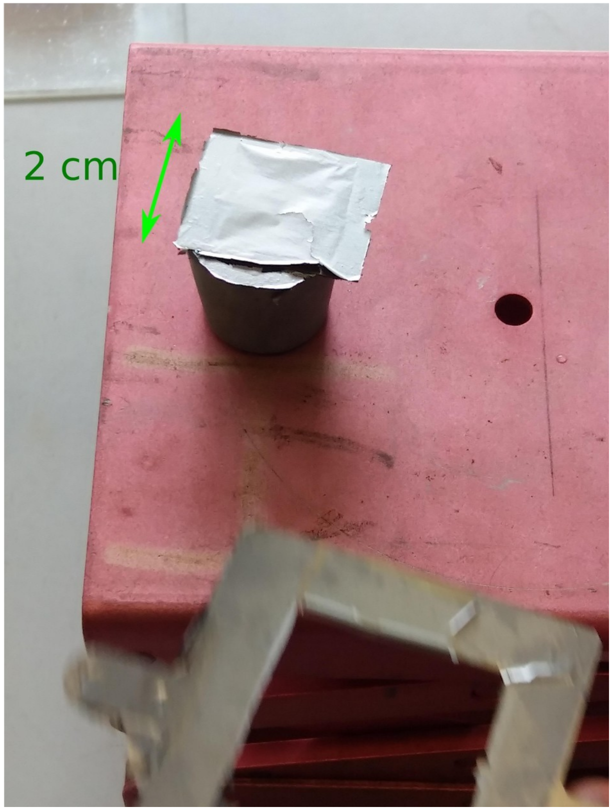
- Selenium
  - thickness of 5 mg/cm² desired
  - planning to roll between gold layers
  - 1 µg/cm² gold backing to dissipate waste heat

- Germanium
  - production of germanium layer of >150 µg/cm² via evaporation
  - stacking of ~20 layers up to desired thickness of 3 mg/cm²
  - frst successful tests with natural germanium at IKP Cologne
  - fnal production at IKP Darmstadt in collaboration with Gabriel Schaumann

Germanium Test







Outline

- **Nuclear structure and 0νββ decay**
  - Infuence of deformation
  - Investigation of nuclear shapes
  - B03 photon scattering ($^{82}Se/^{82}Kr$, $^{150}Sm/^{150}Nd$)
  - B03 electron scattering ($^{76}Ge/^{76}Se$)

- **Nuclear structure and WIMPs**
  - B03 electron scattering ($^{129}Xe/^{131}Xe$)

Motivation

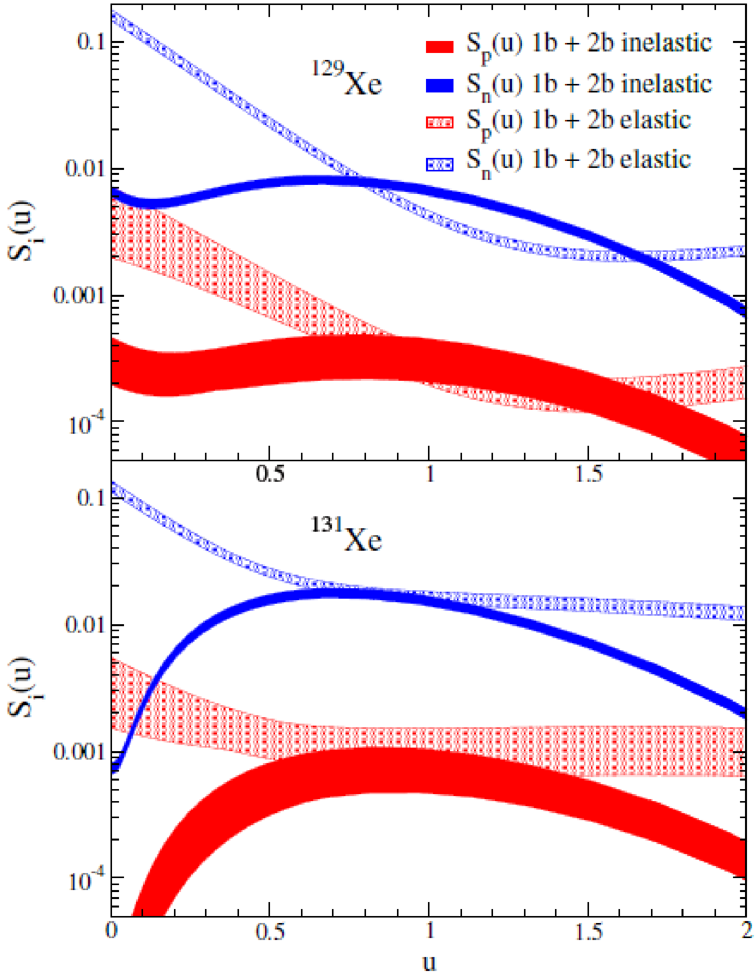
- weakly interacting massive particles (WIMPs) as candidates for dark matter
- attempt to detect via elastic and inelastic scattering off nuclei
- promising detector material liquid xenon
- XENON100 collaboration provides limits for WIMP-nucleon cross section
- measurement of form factors in ^{129}Xe and ^{131}Xe
- providing crucial information for dark matter detection

130Ba ≥3.5E+14 Y 0.106% 2ε	131Ba 11.50 D ε: 100.00%	132Ba >3.0E+21 Y 0.101% 2ε	133Ba 3841 D ε: 100.00%	134Ba STABLE 2.417%
129Cs 32.06 H ε: 100.00%	130Cs 29.21 M ε: 98.40% β-: 1.60%	131Cs 9.689 D ε: 100.00%	132Cs 6.480 D ε: 98.13% β-: 1.87%	133Cs STABLE 100%
128Xe STABLE 1.910%	129Xe STABLE 26.40%	130Xe STABLE 4.071%	131Xe STABLE 21.232%	132Xe STABLE 26.909%
127I STABLE 100%	128I 24.99 M β-: 93.10% ε: 6.90%	129I 1.57E+7 Y β-: 100.00%	130I 12.36 H β-: 100.00%	131I 8.0252 D β-: 100.00%
126Te STABLE 18.84%	127Te 9.35 H β-: 100.00%	128Te 8.8E+18 Y 31.74% 2β-: 100.00%	129Te 69.6 M β-: 100.00%	130Te >5E+23 Y 34.08% 2β-: 100.00%

http://www.nndc.bnl.gov/

Spin-dependent Cross Section

- spin-dependency of WIMP-nucleon interaction unknown
- if spin-dependent, only odd mass number Xe isotopes interact
- large-scale shell-model calculations
- form factors for spin-dependent interaction
- signifcant contribution from *inelastic* WIMP-nucleon scattering
- at low momentum transfer ~0.5 fm^{-1}
- range of operation of S-DALINAC



L. Baudis *et al.*, Phys. Rev. D 88, 115014 (2013)

Electron Scattering Experiments at LINTOTT

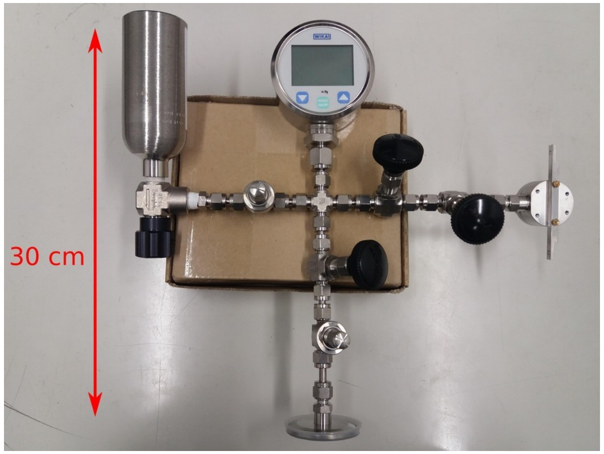
TECHNISCHE UNIVERSITÄT DARMSTADT

- utilizing exceptional energy resolution in energy-loss mode of LINTOTT-spectrometer
- measuring form factors for gs and frst excited states in ^{129}Xe and ^{131}Xe at 40 and 80 keV resp.
- count rate of ~1/s at 93° for 80 MeV beam energy

Status LINTOTT Experiments

TECHNISCHE
UNIVERSITÄT
DARMSTADT

- LINTOTT-spectrometer ready for operation
- ^{129}Xe and ^{131}Xe targets ready



- test beam on target within next weeks
- extended experiments either following or planned for second quarter 2018

Summery and Milestones

- achieved
  - ^{150}Sm measurement and analysis completed
  - ^{82}Se/^{82}Kr measurement completed and presented
  - ^{150}Nd measured

- in preparation
  - ^{100}Mo, ^{129}Xe and ^{131}Xe purchased and ready for operation
  - ^{76}Ge and ^{76}Se target production tests
  - ^{100}Ru to be borrowed at short notice